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THE SIGNIFICANCE OF THE TIME INTERRELATIONSHIPS IN BALLISTOCARDIOGRAPHIC ANALYSIS

/Following is a translation of an article by Ye. V. Erina entitled "O Znachenii Izucheniya Vremennykh Sootnosheniy pri Analize Ballistokardiogramm" (English version above) in Terapevticheskiy Arkhiv (Therapeutic Archives), Vol. 32, No. 5, Moscow, 1960, pages 77-85./

From the Institute of Internal Medicine of the Academy of Medical Sciences USSR (Director-Professor A.L. Myasnikov, active member of the Academy of Medical Sciences USSR).

In the present work we first had the aim of determining the degree to which the use of ballistocardiography can assist the early diagnosis of arteriosclerosis of the aorta and particularly of coronary arteriosclerosis. Subsequently, we attempted to clarify the general abnormalities in the mechanical work of the heart which can be demonstrated by means of an analysis of the time interrelationships of the ballistocardiograms.

Considerable material in the literature has been devoted to the study of the qualitative changes in ballistocardiograms in coronary arteriosclerosis and to attempts to distinguish typical pathological tracings. The material on the study of the time intervals in various

diseases of the heart is the same (Lin Cheng, V.L. Karpman and G.V. Sadovskaya, Ye.R. and G.I. Sidorenko and others). A number of authors have expressed doubt as to the expediency of such an analysis.

Many authors (Scarborough and co-authors, Smith, Pierce and co-authors, Sebastiani and co-authors, and others) made a study of the time intervals in healthy persons. The factual data which they presented are sometimes different, because instruments of different designs were used by all.

We investigated 428 patients, whom we divided into three groups.

In the first group there were 122 patients with hypertension included, in the first and second stages without any clinical signs of arteriosclerosis; the second group consisted of 154 persons in whom hypertension was associated with arteriosclerosis of the blood vessels in different locations. The third group was comprised of 152 patients with coronary arteriosclerosis without hypertension.

We took a speed ballistocardiogram by means of Dock's electromagnetic feeler on a two-channel ink-writing electrocardiograph. Qualitative analysis of the ballistocardiograms was made by the Brown classification with some additions proposed by Lin Cheng and us. They took into consideration the qualitative changes of the various ballistocardiographic waves in the absence of any pronounced

respiratory variations in the wave amplitude (in the second- and third-degree abnormalities).

The results of the investigation of the time intervals are shown in Table 1.

Table 1

Time Intervals on Ballistocardiogram

Group examined	(1) Число обследованных	(2) Средний возраст обследованных (в годах)	(3) Степень изменения баллистокардиограммы	(4) ВИ	(5)		Средняя
					RH	RI	RI
10 – Здоровые	55	36	0	0,5	0,076	0,135	0,201
11 – Гипертоническая болезнь без атеросклероза							
I стадии	25	33	0,9	0,35	0,082	0,135	0,200
IIA »	55	44	1,8	0,31	0,084	0,136	0,196
IIБ »	42	44	2,1	0,31	0,088	0,137	0,195
12 – Гипертоническая болезнь с коронарным атеросклерозом I стадии							
IIA стадии	16	51	2,3	0,21	0,086	0,133	0,189
IIБ »	24	52	2,6	0,18	0,092	0,140	0,200
IIIA »	33	53	2,7	0,17	0,100	0,139	0,202
13 – Гипертоническая болезнь III стадии с коронарным атеросклерозом III стадии	25	56	3,0	0,15	0,115	0,157	0,230
14 – Гипертоническая болезнь II—III стадии с атеросклерозом аорты	36	55	1,8	0,23	0,085	0,126	0,193
15 – Коронарный атеросклероз I (ишемической) стадии	73	50	2,0	0,24	0,085	0,138	0,201
III (склеротической) стадии							
16 – а) не перенесшие инфаркт миокарда	35	60	3,0	0,19	0,100	0,150	0.215
17 – б) перенесшие инфаркт миокарда	53	53	3,2	0,22	0,106	0,158	0,213
18 – в) кардиосклероз безболевой	10	63	1,7	0,27	0,080	0,138	0.200

KEY: (next page, please)

In the study of the time intervals between the ballistocardiographic waves we considered the main indices the duration of the ballistocardiographic systole (the HK

Table 1
(Cont'd)

5) величина расстояний в секундах							6) $RH \geqslant 0{,}10$ секундам		7) $HK \leqslant 0{,}20$ секундам		9) Отношение HK к RK в %
RK	RL	HK	HI	IJ	JK	KL	8) число больных	%	8) число больных	%	
0,296	0,386	0,220	0,060	0,065	0,095	0,090	—	—	—	—	74,3
0,288	0,381	0,206	0,053	0,055	0,088	0,093	3	12	8	32	71,5
0,267	0,381	0,203	0,052	0,060	0,091	0,094	9	16	22	40	70,7
0,290	0,381	0,192	0,049	0,058	0,095	0,091	11	26	25	60	68,2
0,280	0,380	0,194	0,047	0,056	0,091	0,100	4	25	10	62	69,3
0,288	0,380	0,196	0,048	0,060	0,088	0,092	7	30	13	54	68,0
0,290	0,380	0,190	0,039	0,063	0.088	0,090	13	40	25	76	65,5
0,327	0,427	0,212	0,042	0,073	0,097	0,100	16	64	10	40	64,8
0,260	0,363	0,175	0,041	0,067	0,067	0,103	11	30	32	90	67,3
0,300	0,390	0,215	0,053	0,063	0,099	0,090	16	22	18	24	71,6
0,305	0,393	0,205	0,050	0,064	0,091	0,090	18	50	15	41	67,2
0,316	0,410	0,212	0,052	0,055	0,103	0,092	28	53	22	41	66,2
0,286	0,372	0,198	0,050	0,062	0,086	0,084	5	50	5	50	68,7

KEY: 1) No. examined
2) average of subjects (years)
3) degree of change of ballistocardiogram
4) BI
5) Average value of intervals in seconds
6) RH $\geqslant$ 0.10 second
7) HK $\leqslant$ 0.20 second
8) No. of pts
9) ratio of HK to RK in %
10) healthy
11) hypertension without arteriosclerosis, stages I, IIA, IIB
12) Hypertension with coronary arteriosclerosis, stage I stages IIA, IIB, IIIA
13) hypertension, stage III with coronary arteriosclerosis stage III
14) hypertension stages II–III with arteriosclerosis of the aorta
15) coronary arteriosclerosis stage I (ischemic), stage III (sclerotic); 16) a) did not have myocardial infarction; 17) b) had m.i.; 18) c) painless myocardial fibrosis.

interval) and the interval between the beginning of this systole and the R wave of the electrocardiogram (the RH interval).

The ballistocardiograms of 55 healthy people from 19 to 68 years of age were characterized by a considerable distinctness of the waves and a constancy of all the time intervals. The HK interval varied between 0.21 and 0.25 second; the RH interval, from 0.06 to 0.09 second.

The rules and regulations which we determined coincide in principle with data published in 1958 by Lin Cheng; however, the absolute values of the intervals are somewhat different. We are inclined, first of all, to explain this by the fact that feelers of different types (the Smith and Lin Cheng ballistocardiographs) were used as well as different recording instruments. Secondly, we believed that very large average values for RH were recorded by Lin Cheng because he took the first of the two peaks of the split J wave as the H wave. As is well known, the latter is encountered quite often in modified tracings (third-and fourth-degree abnormality according to Brown).

Like Lin Cheng we found that the abnormalities of the ballistocardiogram, reflecting disturbance in the contractile function of the heart, increase in frequency and in their degree of expression with the development of hypertension and the progress of coronary arteriosclerosis. The

same directions of these abnormalities are explained, obviously, by the fact that in both forms of vascular pathology coronary insufficiency of varying degrees exists.

In Table 1 we specially separated a small group of patients in whom the development of arteriosclerotic myocardial fibrosis had proceeded without any clinical signs of coronary insufficiency from the group of patients with coronary arteriosclerosis in the third stage. They showed essential differences in the nature of the ballistocardiographic changes. We shall dwell on the explanation of these characteristics somewhat later.

From Table 1 it is seen that the RH interval gradually and regularly increases in size with the development of hypertension and the superimposition of coronary arteriosclerosis. The same thing is found in patients with coronary sclerosis in various stages.

The greatest values of RH are noted in arteriosclerotic myocardial fibrosis in people who have sustained a myocardial infarction and particularly in patients in whom the myocardial fibrosis is combined with hypertension (the RH in rare cases reached 0.15-0.17 second).

As far as the systolic ballistocardiographic complex is concerned its duration decreased with the development of hypertension. The greatest shortening of the HK interval (0.175 second) was noted in the group of patients with

hypertension and arteriosclerosis of the aorta without any signs of coronary arteriosclerosis. It is noteworthy that qualitative ballistocardiographic changes in these patients were expressed to a considerably lesser degree than in patients with hypertension, stages II and III, which were associated with coronary sclerosis in the ischemic stage.

In 1958, we reported on material concerning the comparison of indices produced by several methods, which assisted in the diagnosis of arteriosclerosis of the aorta (roentgenokymographic data of the thoracic aorta and of the rate of propagation of the pulse wave were compared with the magnitude of the ballistocardiographic systolic complex). We showed quite a distinct parallelism between the indices of these methods, particularly in the last two. This made it possible for us to consider a shortening of the HK to less than 0.20 second a quite reliable sign of reduction in the elasticity of the aorta.

As far as the other time intervals in the ballistocardiogram are concerned the striking constancy of the value of the RL in patients with hypertension in all groups attracts attention, although there were definite differences in the other intervals of the systolic complex.

We did not find any regular shortening in the IJ, which Jones and Goulder considered characteristic of arteriosclerosis of the aorta. However, this shortening was found

quite distinctly with respect to the HI interval (from a normal value of 0.06 second it decreased to 0.039 second in third stage hypertension).

In Table 1 the frequency of the changes in the RH and HK intervals is also presented. As is seen from the data presented in it, the frequency of lengthening of the RH interval increases with the progress of hypertension, coronary arteriosclerosis and the development of myocardial fibrosis.

Shortening of the HK was found in 62-76 percent of the patients with hypertension, stages II and III with signs of coronary arteriosclerosis, and in 90 percent of the patients with clinically determinable isolated arteriosclerosis of the aorta.

It is important to note that in patients with hypertension without any clinical signs of arteriosclerosis arteriosclerosis of the aorta very frequently was found by results of investigation using a number of methods. Specifically, according to the ballistocardiographic data in patients with hypertension, stages IIA and IIB, it was found, respectively, in 40 and 60 percent of the cases.

We considered such data the very initial signs of the preclinical stage of development of arteriosclerosis of the aorta.

It was interesting to study the frequency of these

signs in young patients with hypertension (under 40 years of agé). As Professor A.L. Myasnikov indicated at the First All-Russian Congress of Internists, only pathological investigations give us, at the present time, some idea of the early manifestations of arteriosclerosis. They showed that lipoidosis of the aorta is encountered even at the age of 25-30, and this may be considered a "prologue of arterio-sclerosis".

In our investigations the signs of decrease in aortic elasticity, that is, shortening of the HK, were found in solitary cases among patients under 30 years of age and in one-third of the patients from 31 to 40 years of age (Table 2). This change correlates with the increase in the rate of propagation of the pulse wave in the majority of these patients. Therefore, by means of ballistocardiography the premorbid stage of arteriosclerosis of the aorta may be demonstrated.

The question arises, does not the shortening in the systolic complex, HK, in young patients with hypertension depend on hypertrophy of the left ventricle--this early and typical sign of hypertension? For the purpose of throwing light on this we examined 15 athletes from 19 to 40 years of age with a normal blood pressure and a pronounced left ventricular hypertrophy. None of them showed a shortening of the HK interval, which varied from 0.22 to 0.26 second

Table 2

Ballistocardiographic Time Intervals in Young Hypertensive Patients and in Athletes

Group of subjects	No examined	Average age (years) Средний возраст (в годах)	Degree of change on ballistocardiogram Степень изменения баллистокардиограммы	Average intervals in seconds						RH>.1 sec No of pts. RH > 0,10 секунам число больных		HK<.2 sec. HK ≤ 0,20 секунам число больных	
				RH	RI	RJ	RK	RL	HK	absolute абс.	%	absolute абс.	%
Здоровые (19—40 лет)	45	32	0	0,076	0,134	0,200	0,294	0,384	0,218	—	—	—	—
Больные гипертонической болезнью													
(19—30 лет)	22	25	0,86	0,084	0,145	0,210	0,310	0,400	0,226	3	12	3	12
(31—40 лет)	32	36	1,27	0,085	0,135	0,195	0,288	0,375	0,203	4	12,5	12	33
Спортсмены	15	31	0	0,08	0,140	0,212	0,312	0,413	0,232	—	—	—	—

Healthy (19-40)
Hypertensive pts
(19-30 yrs.)
(31-40 yrs.)
Athletes

This is the same average value for HK, equal to 0.232 second, which was found by V.V. Barabanshchikov and co-authors in the examination of 104 athletes.

Therefore, isolated hypertrophy of the left ventricle was characterized by a certain lengthening of ballisto-cardiographic systole, and the combination of hypertrophy with a reduction in the elasticity of the aorta, with a shortening of it. In addition, the ballistocardiograms of athletes were different from the ballistocardiograms of healthy persons who did not engage in athletics in the relatively tall and broadened L wave.

As far as the change in the HK interval is concerned, in patients with coronary arteriosclerosis (see Table 1), shortening of it was encountered less often than in hyper-tension. The same thing was noted in patients with hyper-tension and myocardial fibrosis, in whom a normal or even widened HK interval (to 0.30 second) was found. At the same time, according to data obtained by means of other instrumental methods, arteriosclerosis of the aorta was diagnosed in all these patients.

An analysis of the causes of this discrepancy in the criteria of various methods and a comparison of this dis-crepancy with the clinical data showed that lengthening of the systolic portion of the ballistocardiogram in patients can be considered an index of serious deterioration in the

contractile function of the myocardium and the development of myocardial fibrosis. In the majority of cases this change was associated with a considerable delay in the onset of ballistocardiographic systole and pronounced qualitative changes in the tracings (third-fourth-degree according to Brown) with a marked reduction of the amplitude and splitting of the waves, particularly the H, I, K (Fig. 1).

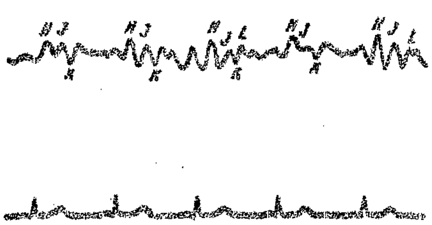

Fig. 1. Ballistocardiogram of Patient S., age 51 (Diagnosis: Arteriosclerotic Myocardial Fibrosis; Chronic Coronary Insufficiency) Third-degree changes. RH=0.14 second; HK=0.24 second.

In the majority of patients with myocardial fibrosis a very great variation was noted both in the configuration of the systolic complexes and in all the time intervals in various phases of respiration (shortening in the phase of inspiration and marked lengthening in the phase of expiration; the differences reached 0.08 second). We consider these changes an additional unfavorable sign indicating functional insufficiency of the cardiac muscle.

Essential changes in the nature of the ballistocardiographic changes were found in patients with arteriosclerotic myocardial fibrosis who had never suffered from anginal attacks (Fig. 2). Among them pronounced ballistocardiographic changes were encountered less often. While tracings showing third- and fourth-degree abnormalities according to Brown were noted in the first stage of arteriosclerosis in 40 percent of the patients and in 81 percent in the third stage, in painless myocardial fibrosis they were noted in only 20 percent.

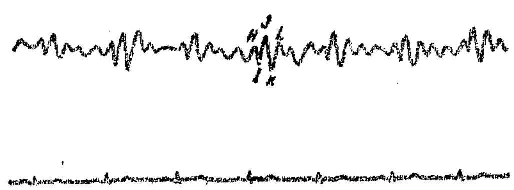

Fig. 2. Ballistocardiogram of Patient K., age 67 (Diagnosis: Arteriosclerotic Myocardial Fibrosis, Painless Form). Zero degree change according to Brown. RH=0.11 second; HK=0.20 second

As far as the frequency of changes in the basic time intervals is concerned, just as in the case of the other patients with myocardial fibrosis, in half of them a lengthening of the RH interval and shortening of the HK interval were found. This is evidence, in our opinion, of the fact that varying degrees of coronary insufficiency are most important in the origin of the ballistocardiographic changes.

The determination of certain rules and regulations in

the change in the time intervals confronted us with a new problem, namely, whether various intervals reflect certain phases of cardiac activity. From the physiological viewpoint, is it justifiable to designate the HK interval "hemodynamic systole", as some authors do (Sebastiani and co-authors, de Simone and others)? In order to clarify this, we recorded a ballistocardiogram and a phonocardiogram simultaneously.

We succeeded in determining that the peak of the H begins somewhat after the onset of the first sound; the K wave always precedes the onset of the second sound, and the end of it almost coincides with the L peak. However, with the use of a low-frequency phonocardiograph, using an ink-writing "Galileo" electrocardiograph, we can judge only the beginning of the first sound, caused by the closure of the mitral valve, but we cannot accurately determine the moment of opening of the semilunar valves, that is, the end of the phase of isometric tension and the beginning of expulsion of blood. We were specifically interested in the latter.

A number of authors, including Ye.B. Babskiy and V.L. Karpman, point out that the phases of the cardiac cycle cannot be analyzed from the ballistocardiogram in contrast to the dynamocardiogram because they record different mechanical processes.

These conclusions were made on the basis of a

calculation of the ballistocardiographic intervals between the displacements recorded by means of a low-frequency dynamometric table. However, a comparison of our factual data computed from a speed ballistocardiogram (with the use of a Dock feeler), with the duration of the phases of cardiac activity according to the data of dynamocardiography, proves the opposite.

In Table 3 the time intervals on the ballistocardiogram are shown for healthy persons and the dynamocardiographic data. One cannot help but note the striking agreement of the values which have the same physiological significance. Thus, the systolic complex HK in healthy persons under 40 years of age is identical with the expulsion phase calculated from the dynamocardiogram of healthy persons of the same age. The duration of mechanical systole of the ventricles and the RK interval are almost equal also. The same agreement of values with respect to the phase of isometric tension and the RH interval also exists. This correlation is reinforced by data of pericardiac rheography, according to which the tension phase, on the average, is equal to 0.075 second (Yu.T. Pushkar').

This agreement once again confirms Wiggers' principle that the peak of the R quite accurately reflects the onset of mechanical systole. In this connection, it is not so convenient to calculate from the Q wave (QH), because it

includes the propagation time of the electrical excitation through the cardiac muscle. Therefore, we considered a calculation of the RH interval from the ballistocardiogram important, since it permits us to demonstrate the various relationships between the time of electrical excitation and the mechanical response of the cardiac muscle. We agree with other authors (Sebastiani, Lin Cheng and others) that RH is the most important interval in the physiological sense: It gives us an idea of the time which is required by the cardiac muscle for the conversion of the energy of contraction into the energy of pressure and expulsion of blood.

It might be expected that the RH interval would be lengthened in various heart diseases associated with a weakening of the cardiac muscle. Our data confirm this situation with regard to patients with hypertension and coronary arteriosclerosis.

Table 3

Ballistocardiographic Intervals in Healthy Persons

(1) Возраст обследованных (в годах)	(2) Число обследованных	(3) Степень изменения баллистокардиограммы	ДК	БИ	(4) Средняя продолжительность расстояния в секундах: RH	RI	RJ	RK	RL	HK	(5) Отношение HK к RK в %
19—29	10	0	1,54	0,571	0,072	0,131	0,201	0,290	0,390	0,218	75,1
30—39	35	0	1,75	0,473	0,078	0,135	0,200	0,296	0,385	0,218	73,6
40—68	10	0,4	2,49	0,367	0,077	0,137	0,203	0,302	0,392	0,225	74,5
(6) В среднем			1,9		0,076	0,136	0,201	0,296	0,396	0.22	74,3

(7) Фаза изометрического напряжения равна . . . . 0,074 секунды (11) До данным динамокардиографии
(8) Фаза изгнания крови равна . . . . 0,218 »
(9) Систола желудочков равна . . . . 0,292 »

(10) $\frac{\text{Время изгнания}}{\text{Систола желудочков}} = 74,6\%$

(12) Обозначения. ДК — дыхательный коэффициент; БИ — баллистокардиографический индекс.

KEY: 1) Age of subjects (years); 2) no. of subjects; 3) degree of ballistocardiographic change; 4) average interval in seconds; 5) ratio of Hk to RK in percent; 6) on the average; 7) isometric tension phase equal to 0.074 sec.; 8) blood expulsion phase equal to 0.218 sec.; 9) ventricular systole equal to 0.292 sec.; 10) expulsion time divided by ventricular systole = 74.6 percent; 11) according to dynamocardiographic data; 12) Key: RQ--respiratory quotient; BI--ballistocardiographic index.

We have attempted to convince ourselves of the fact that the peak of the H coincides with the end of the tension phase and the beginning of expulsion of blood from the heart by means of a simultaneous recording of a ballistocardiogram, electrocardiogram, and a piezogram of the carotid artery; variations of pressure in the aorta reflect on the latter, and the onset of the rapid expulsion of blood is very distinctly demonstrated. We calculated the time from the R wave of the electrocardiogram to the beginning of the abrupt rise in pressure in the carotid artery and designated it R-ej.

In 50 persons whom we examined for this purpose the R-ej interval, on the average, was 0.095 second; the RH, 0.085 second (Fig. 3). As is seen, R-ej is very slightly different from RH, by 0.01 second (from 0 to 0.02 second), that is, the peak of the H almost coincides with the beginning of expulsion of blood into the aorta. The fact that H somewhat outstrips the rise in pressure in the carotid artery is natural, because systole of the right ventricle begins earlier than that of the left. In patients with arteriosclerosis of the aorta this interval approaches 0.

Sometimes the rise in the carotid pulse preceded the split peak of the H, which might indicate a delay in expulsion of blood from the right ventricle.

Therefore, through the recording of the pulse tracing

of the carotid artery it is possible to check on and supplement the ballistocardiographic data and determine the degree of lack of coordination in the cardiac activity (asynchrony of expulsion from the ventricles). This proves that the ballistocardiographic method can to a certain degree be used for the objective evaluation of the phases of the cardiac cycle.

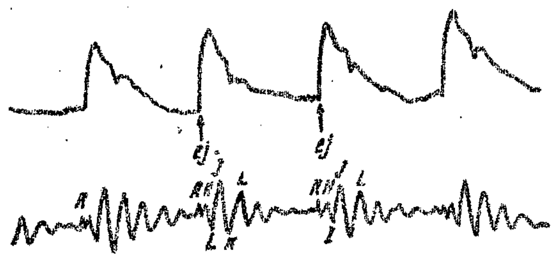

Fig. 3. Simultaneous Recording of Piezogram of Carotid Artery and Ballistocardiogram (with Superposition of R wave of EKG) in Healthy Person, age 18. R-H=0.085 second; R-ej=0.095 second; RI=0.140 second.

This conclusion is in agreement with the observations of Sebastiani and others, who on the basis of a comparison of the ballistocardiographic and electrokymographic data concluded that the QH interval (or RH interval) can serve as a measure of the tension phase of the ventricles.

We considered the HK interval as corresponding to the period of expulsion from the ventricles; the K-second sound-interval, to the protodiastolic period; and the RK, to mechanical systole. This is also in agreement with the

opinion of Sebastiani, who considers it possible to evaluate the duration of mechanical systole by the G-K interval and suggested a formula similar to Basett's formula for deriving the absolute values in accordance with the rate of cardiac contraction.

Since the G wave of the ballistocardiogram is demonstrated with difficulty and is very closely related temporally with the R wave of the electrocardiogram, we believe that the same thing can be done by calculating the RK. The normal values of these intervals are quite similar.

In clinical practice it is not always enough to know the absolute values of the duration of mechanical systole, because it changes in dependence on the cardiac rate. For the purpose of evaluating the functional condition of the cardiac muscle the relative indices are of greater importance, for example, the ratio of the duration of the expulsion phase from the ventricles to the duration of mechanical systole. It characterizes the intrasystolic index. A reduction of it attests to the low degree of efficacy of cardiac contraction. According to the data of V.L. Karpman, normally it amounts to 74.6 percent; according to our data, 74.3 percent.

With the development of hypertension and arteriosclerosis a gradual lengthening occurs in mechanical systole and a reduction of this index. The lowest intrasystolic index

occurred in patients with hypertension in the third stage with myocardial fibrosis who had had a myocardial infarction. This index is in good correlation with clinical observations which attest to the considerable frequency of development of cardiac insufficiency in such patients.

Conclusions

1. Study of the time relationships is a very valuable method which considerably supplements the characterization of qualitative changes in the ballistocardiogram and broadens the diagnostic possibilities of ballistocardiography.

2. The degree of increase in the RH interval, that is, the delay between the beginning of hemodynamic systole after electrical systole, is of diagnostic significance in hypertension and arteriosclerosis and reflects the degree of development of myocardial fibrosis.

3. Shortening of the systolic complex (HK interval) is a reliable sign of arteriosclerosis of the aorta.

4. A comparison of our data with the data of dynamocardiography showed that ballistocardiography can be used for the determination of the duration of certain phases of the cardiac cycle (phases of tension and of expulsion of the ventricles).

5. The intrasystolic index, that is, the ratio between the period of expulsion and the entire mechanical systole

is an important additional criterion which makes it possible objectively to evaluate the strength of cardiac contractions in various cardiovascular diseases.

6. The diagnostic possibilities of ballistocardiography increase with the simultaneous recording of the other hemodynamic processes, particularly variations of pressure in the carotid artery and of the heart sounds.

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